Revisiting Humidity Ramp Protocols for Assessing Human Heat Tolerance

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Word count: ~4,550 words (references, figure/table captions excluded)

Running head: Revisiting humidity ramp protocols

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Abstract (248 words)

Background: Humidity ramp protocols are widely used to determine human heat tolerance, yet it remains unclear how the rate and duration of environmental changes affect the apparent inflection in core temperature (T_{cr}). This study integrates theoretical modeling and empirical trials to examine how the temporal structure of humidity-ramp protocols affects the accuracy of estimated critical environmental limits (CELs).

Methods: A first-order model was developed to describe T_{cr} response to stepwise changes in equilibrium core temperature ($T_{cr,eq}$) determined by ambient humidity at a fixed dry-bulb temperature. Analytical solutions were derived for discrete humidity steps of duration Δt, and sensitivity analyses were conducted across physiologically plausible time constants (τ). Fourteen healthy young males (23.5±1.8 yrs) completed two randomized trials in a 42 °C heat chamber: 1) *Slow-ramp*: 4-hour equilibration at 40% RH followed by +6% RH/hour for 2 h, then +3% RH/hour (40–61% RH); and 2) *Aggressive-ramp*: 30 min equilibration followed by +2% RH every 5 min (28–88% RH). Rectal and skin temperatures, heart rate, and perceptual ratings were recorded continuously.

Results: When $\Delta t/\tau \ll 1$, residual disequilibrium between $T_{cr,eq}$ and T_{cr} accumulates, producing accelerated rises in T_{cr} and premature CELs. Longer dwell durations (≥ 1 hour per step) allowed near-equilibrium responses, yielding physiologically valid thresholds. Empirically, shorter ramp durations shifted apparent CELs downward by 3.4±1.9 °C.

Conclusion: Dynamic lags from short dwell intervals lead to the systematic underestimation of heat tolerance. Reliable determination of CELs requires either prolonged steady-state exposures or dynamic correction models validated against such conditions.

Keywords: humidity ramp; thermoregulation; rectal temperature; critical environmental limits; heat tolerance; prolonged exposure

Key points

- Humidity-ramp protocols are widely used to identify the transition from compensable to uncompensable heat stress, but their reliability is fundamentally constrained by the body's thermal response time.
- A first-order dynamic model demonstrates that the ratio of step duration (Δt) to the physiological time constant for core temperature equilibration (τ) determines whether true steady-state conditions are achieved.
- When $\Delta t/\tau \ll 1$ (e.g., 5–10 min steps), dynamic lags accumulate between environmental and physiological states, producing premature inflection points that systematically underestimate human heat tolerance.
- Empirical data confirm that conventional short-duration ramps fail to capture true critical limits, while longer ramps ($\Delta t \geq 1$ h; $\Delta t/\tau \approx 0.3$–$0.5$) approach equilibrium but remain less robust than steady-state exposures.
- Accurate determination of critical environmental limits requires either prolonged steady-state exposure or validated dynamic correction models; uncorrected ramp protocols should not be used as stand-alone methods.

Introduction

As global temperatures rise and extreme heatwaves become increasingly frequent, intense, and prolonged (Rahmstorf and Coumou 2011), understanding the physiological limits of human heat tolerance has never been more crucial (Pandolf 1997; Taylor 2014; Bouchama 2025; Wang 2025a). A central challenge is defining the critical environmental limits (CELs)—combinations of ambient temperature and relative humidity (RH) beyond which the human body can no longer maintain thermal equilibrium. Crossing these limits results in uncompensable heat stress, characterized by a rapidly elevation in core temperature (T_{cr}) and an increased risk of heat-related illnesses (Sherwood and Huber 2010; Kenney et al. 2004).

A widely used experimental approach to identify these critical thresholds is the *humidity ramp protocol* (also known as the *thermal-step* or *core temperature inflection-point protocol*), first introduced by Belding and Kamon (1973). In its classical form, this method progressively increases relative humidity in fixed increments—typically 1 mm Hg every 10 minutes—following an initial 60-minute core temperature stabilization period at a constant air temperature and low humidity (Kamon 1976). The point at which T_{cr} rises uncontrollably is interpreted as the transition from compensable to uncompensable heat stress. Recent studies have adopted modified versions of this approach to determine CELs across populations and environmental conditions (Cottle et al. 2022; Vecellio et al. 2022; Wolf et al. 2021; Wolf et al. 2022; Wolf et al. 2023). However, reported humidity-ramp protocols differ substantially in their initial stabilization durations, step magnitudes, and ramp rates. For instance, some studies implemented a 30-minute stabilization phase followed by either a 1 mm Hg increase in ambient water vapor pressure or a 3% increase in relative humidity every 5 min (Cottle et al. 2022; Vecellio et a. 2022; Wolf et al. 2021; Wolf et al. 2022; Wolf et al. 2023), whereas others employed 1 °C ambient temperature or 1 mm Hg increments every 10 min (Belding and Kamon 1973; Kamon 1976). More recently, Meade et al. (2024) adopted a 70-minute equilibration period followed by 3% RH (i.e., ~1.85 mm Hg) increments every 10 minutes.

Despite broadly similar participant characteristics and testing protocols, reported CELs vary markedly, ranging from approximately 26 °C to 33 °C in young adults with metabolic rates of 1.3-1.5 Mets (Cottle et al. 2022; Vecellio et al. 2022; Wolf et al. 2021; Wolf et al. 2022; Wolf et al. 2023, Meade et al. 2024). Such wide variability raises a fundamental methodological concern: does the arbitrary selection of ramp rate and step duration influence the accuracy of the predicted critical environmental limits?

The traditional ramp approach implicitly assumes that the human thermoregulatory system equilibrates to each environmental step before the next begins. In practice, however, the dwell time per step—typically 5–10 min—may be insufficient for the body to achieve a new steady state, particularly under conditions of high thermal inertia. This raises an essential question: does the observed inflection in T_{cr} truly represent the physiological onset of uncompensable heat stress, or merely a transient lag—a dynamic mismatch between the body's actual thermal state and its moving equilibrium?

To address this, we hypothesized that the apparent inflection point in T_{cr} during humidity ramp protocols is influenced by the duration of each step. Specifically, shorter steps may induce a premature and distorted onset of uncompensable heat stress due to incomplete thermal equilibration, whereas longer steps allow near full stabilization, yielding more accurate steady-state estimates. To test this hypothesis, the present study examines how stepwise duration affects the apparent critical inflection point in T_{cr} during humidity ramp protocols. By systematically varying the rate of humidity increase under constant dry-bulb temperature conditions, we aim to elucidate how the temporal structure of the humidity ramp affects the transition to uncompensable heat stress. Furthermore, we introduce a simplified first-order thermal response model to describe T_{cr} dynamics in relation to environmental humidity. Through this combined empirical-modeling approach, we aim to clarify how ramp timing distorts apparent critical limits and to propose evidence-based guidelines for designing physiologically valid humidity ramp protocols.

Methods

Model derivation and assumptions

The temporal evolution of core temperature (T_{cr}) during progressive humidity changes was derived from the first principles of whole-body heat balance. The human body is modeled as a single, lumped thermal compartment that exchanges heat with the surrounding environment via convection, radiation, and evaporation. At any time t, the rate of body heat storage equals the rate of metabolic heat production minus the combined dry (convective and radiative) and evaporative heat losses (Gagge and Gonzalez 2011)

$$C\frac{dT_{cr}}{dt} = \dot{M} - \dot{W} + \dot{Q}_{res} - \dot{Q}_{skin} \qquad \text{Eq.(1)}$$

where, C is the effective whole-body heat capacity (J/°C); $\dot{M}$ is metabolic heat production rate (W); $\dot{W}$ is external mechanical work rate (Watt; $\dot{W}$≈0 watt under seated conditions); $\dot{Q}_{res}$ and $\dot{Q}_{skin}$ are respiratory and skin heat exchange rates (W), respectively.

The net heat loss through the skin surface can be expressed as the sum of convective, radiative, and evaporative fluxes (Gagge and Gonzalez 2011)

$$\dot{Q}_{skin} = \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{evap} \qquad \text{Eq.(2)}$$

with $\dot{Q}_{conv} = h_c A_s (T_{sk} - T_a)$, $\dot{Q}_{rad} = h_r A_s (T_{sk} - T_r)$, and $\dot{Q}_{evap} = h_e A_s (p_{sk} - p_a)$

where, h_c, h_r, and h_e are the convective, radiative, and evaporative heat transfer coefficients (W/m²/°C), respectively; A_s is body surface area (m²); T_{sk} is mean skin temperature (°C); T_a and T_r are ambient air (dry-bulb) and mean radiant temperatures(°C), respectively; p_s and p_a are the water vapor pressures at the skin surface and in ambient air (Pa), respectively.

Under the classical humidity ramp experimental conditions—where air temperature is held constant and relative humidity progressively increases—metabolic heat production ($\dot{M}$) and respiratory heat exchange ($\dot{Q}_{res}$) can be treated as approximately constant. Consequently, variations in total heat loss are primarily governed by humidity-dependent changes in the potential for sweat evaporation (Brebner et al. 1958; Clifford et al. 1959). To obtain a tractable representation of the system's transient thermal response, the net heat exchange was linearized around the steady-state operating point:

$$\dot{M} - \dot{W} + \dot{Q}_{res} - \dot{Q}_{skin} \approx -k[T_{cr}(t) - T_{cr,eq}(t)] \qquad \text{Eq.(3)}$$

where, $T_{cr,eq}$ is the equilibrium core temperature that would be achieved if the environment were held constant indefinitely (°C). k is an effective whole-body heat transfer coefficient (W/°C)—the lumped sum of convective, radiative, and evaporative heat conductances, modulated by physiological control of skin blood flow and sweating. Mathematically, k represents how efficiently excess body heat is dissipated when T_{cr} exceeds equilibrium, which is read as:

$$k = -\left.\frac{d(\dot{M} - \dot{Q}_{loss})}{dT_{cr}}\right|_{eq} \qquad \text{Eq.(4)}$$

where, $\dot{Q}_{skin}$ denotes the sum of convective, radiative, evaporative, and respiratory heat losses, i.e., $\dot{Q}_{skin} = \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{evap} + \dot{Q}_{res}$.

Substituting Eq.(3) into the whole-body energy balance [i.e., the Eq.(1)] yields

$$C\frac{dT_{cr}(t)}{dt} = -k\left[T_{cr}(t) - T_{cr,eq}(t)\right] \quad \text{Eq.(5)}$$

This relation shown in Eq.(5) indicates that the rate of core temperature change is proportional to the instantaneous deviation from the environment-defined equilibrium value.

Dividing both sides of the Eq.(5) by C and defining the time constant $\tau = \frac{C}{k}$ gives

$$\frac{dT_{cr}(t)}{dt} = -\frac{1}{\tau}\left[T_{cr}(t) - T_{cr,eq}(t)\right] \quad \text{Eq.(6)}$$

The thermal time constant τ characterizes the rate at which T_{cr} approaches equilibrium following an environmental step change. Eq.(6) describes a linear first-order low-pass response with time constant τ that encompasses both passive body heat storage and active thermoregulatory feedback. The time constant τ represents the characteristic response time for T_{cr} to approach a new equilibrium following an environmental step change in relative humidity (RH).

During each discrete humidity step of duration Δt, the equilibrium temperature $T_{cr,eq}$ is assumed to remain constant. The analytic solution of Eq.(6) for a step initiated at time $t = t_n$ is given by

$$T_{cr}(t) = T_{cr,eq,n} + \left[\left(T_{cr}(t_n) - T_{cr,eq,n}\right) \times e^{-\frac{(t-t_n)}{\tau}}\right] \quad \text{Eq.(7)}$$

At the end of each step ($t_{n+1} = t_n + \Delta t$):

$$T_{cr,n+1} = T_{cr,eq,n} + (T_{cr,n} - T_{cr,eq,n}) \times e^{-\frac{\Delta t}{\tau}} \quad \text{Eq.(8)}$$

Eq.(8) quantifies how far the body approaches equilibrium within each step. If Δt is sufficiently small, Eq.(8) can be approximated using the Euler form (Stewart 2015)

$$T_{cr,n+1} \approx T_{cr,n} + \frac{\Delta t}{\tau} \times (T_{cr,eq,n} - T_{cr,n}) \quad \text{Eq.(9)}$$

When the environmental humidity change is rapid (i.e., $\frac{\Delta t}{\tau} \ll 1$), the system (i.e., human body) does not equilibrate between steps, and residual thermal disequilibrium accumulates, expressed as

$$\left.\frac{dT_{cr}}{dt}\right|_{n+1} > \left.\frac{dT_{cr}}{dt}\right|_{n} \qquad \text{if} \quad \frac{\Delta t}{\tau} \ll 1 \quad \text{Eq.(10)}$$

where, $\left.\frac{dT_{cr}}{dt}\right|_{n+1}$ and $\left.\frac{dT_{cr}}{dt}\right|_{n}$ denote slopes of the core temperature change at the (n+1)th and nth step of a humidity ramp. It can therefore be deduced from Eq.(10) that the progressive acceleration in T_{cr} rise results in an apparent inflection, which reflects dynamic lag rather than true uncompensable heat stress. Detailed mathematical justification can be found in Supplemental Material.

Physiological verification study

Sample size and power calculation

The primary comparison focused on differences in ambient partial water vapor pressure (P_{air}) at the inflection point of core temperature (T_{cr}) between the aggressive-ramp and slow-ramp protocols. Assuming a large expected effect size (Cohen's d = 0.8) and a paired-samples t-test, a minimum of 12 participants was required to achieve 80% statistical power at a two-tailed significance level of 0.05. This calculation assumed low within-subject variability in P_{air} at the point of T_{cr} inflection point. To account for potential attrition, sixteen participants were initially recruited, and two withdrew after completing their first trials for individual reasons.

Participants and ethical approval

Fourteen healthy young males (age: 23.5±1.8 yrs, height: 1.74±0.05 m, weight: 69.5±7.9 kg, body surface area: 1.83±0.12 m^2, body mass index: 22.9±2.0 kg/m^2), all nonsmokers and free from cardiovascular, metabolic, or thermoregulatory disorders, volunteered for this study. Written informed consent was obtained from all participants prior to testing. The study was approved by the Institutional Review Board (IRB) of Xi'an University of Science and Technology (Approval No. XUST-IRB225034) and conformed to the principles of the Declaration of Helsinki.

Experimental design

Upon arrival, participants provided a urine sample to assess hydration status. Testing commenced only if urine specific gravity (USG) was ≤1.020, indicating euhydration (Oppliger et al. 2005). Participants with USG values above this threshold consumed an isotonic electrolyte solution and were re-tested until euhydration was achieved. Prior to chamber entry, participants confirmed a thermoneutral perception across all body regions, and their initial rectal temperature (T_{cr}) was required to be ≤ 37.1 °C. These procedures ensured that all trials began under comparable baseline hydration and thermal states.

Each participant completed two trials (aggressive-ramp and slow-ramp) in a randomized, counterbalanced order, separated by at least one week. All experiments were conducted in a heat chamber maintained at a dry-bulb temperature of 42 °C. Participants remained seated throughout and engaged in light office tasks (e.g., reading, typing, or using their phones) to simulate minimal metabolic heat production. In the aggressive-ramp protocol, ambient relative humidity (RH) was initially set at 28% for 30 min, followed by a 2% RH increase every 5 min until a termination criterion was reached. In the slow-ramp protocol, participants first underwent a 4-hour equilibration phase at 40% RH, after which RH increased by 6% per hour from the 4th to 6th hour, and by a 3% per hour thereafter until termination criteria were met. **Figure 1** presents a schematic overview of the two humidity-ramp protocols used in this study and the corresponding wet-bulb temperatures observed during each protocol.

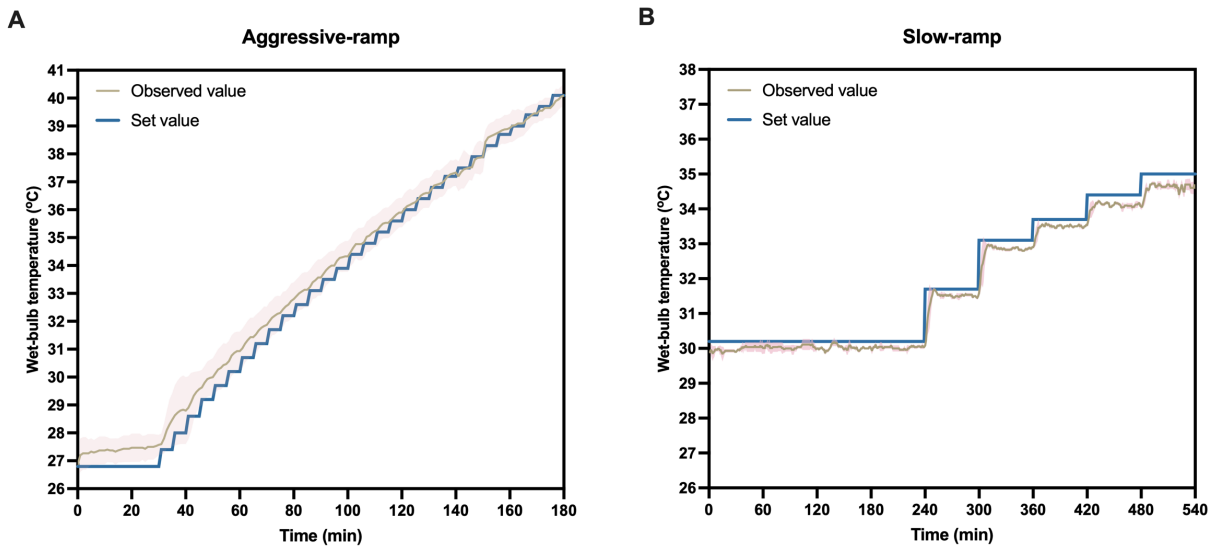

Figure 1 Schematic illustration of the two humidity ramp protocols. **A**, *Aggressive-ramp*: an initial 30-min stabilization at 42°C, followed by 2% RH increments every 5 min until 88% RH (total exposure duration = 180 min); **B**, *Slow-ramp*: an initial 4-hour stabilization at 42°C and 40% RH, followed by 6% RH increments per hour for 2 h (to 52% RH) and then 3% RH increments per hour for up to 3 hours (to 61% RH; total exposure duration = 9 h). The programmed set values (blue lines) and the observed mean wet-bulb temperature with standard deviation (tan line with pink band) are shown for each protocol.

Measurements

Hydration status was determined using a digital hand-held refractometer (PAL-1, Atago Co. Ltd., Tokyo, Japan; accuracy: ±0.2%). Rectal temperature (T_{cr}) was measured using a YSI-401

probe (YSI Inc., Yellow Springs, OH) inserted 10 cm beyond the anal sphincter. Mean skin temperature (T_{sk}) was obtained using iButtons (DS1992L, Maxim Integrated, Sunnyvale, CA; calibrated to accuracy: ±0.2 °C) affixed at the chest, upper arm, thigh, and calf, weighted according to Ramanathan's four-site equation (Ramanathan 1964). Heart rate (HR) was continuously recorded using chest-strap telemetry (Polar Vantage XL, Polar Electro Oy, Finland). Metabolic rate was assessed using a breath-by-breath metabolic system (Calibre Biometrics, Wellesley, MA) for 10 minutes after a 15-minute thermal stabilization period during which participants performed light office tasks in the heat chamber (Van Hooren et al. 2024). Perceptual ratings of thermal sensation, thermal discomfort, skin wetness, and thirst sensation were obtained every 5–10 min using validated scales (**Figure S1**; Wang et al. 2025a). Environmental conditions (dry-bulb temperature and RH) were monitored continuously using three calibrated temperature–humidity data loggers (TH42W-EX, Huahanwei Technology Co. Ltd., Shenzhen, China; temperature accuracy: ±0.1 °C; humidity accuracy: ±1.5%). The loggers were positioned at heights of 0.1 m, 0.6 m, and 1.1 m above the floor. Core and skin temperatures and heart rate were logged at 1-minute intervals throughout all trial phases.

Termination criteria

Trials were immediately terminated if any of the following occurred: 1) $T_{cr} \geq 38.6$ °C; 2) onset of heat-related symptoms (e.g., numbness, dizziness, nausea, or presyncope); or 3) voluntary withdrawal. Environmental adjustments were immediately halted upon termination, and participants were promptly removed from the heat chamber for recovery.

Data analysis

Individual T_{cr} data were smoothed using the *smooth* function with a smoothing parameter (*spar*) of 0.9. The time derivative of T_{cr} (°C/h) was then computed to identify inflection points corresponding to the onset of uncompensable heat stress. The critical humidity limit was defined as the environmental condition at which T_{cr} exhibited a sustained positive acceleration. Comparisons between the two humidity-ramp protocols were performed to determine whether shorter dwell intervals produced systematically lower apparent critical limits. Because each participant completed both protocol trials, differences in critical wet-bulb temperature (T_w) between protocols were analyzed using paired sample *t*-tests, with effect sizes expressed as Cohen's *d*. All statistical analyses were conducted in R version 4.5.1, with significance set at $P < 0.05$. Data are presented as means ± SD (standard deviation) unless otherwise specified.

Inflection point determination

Earlier studies (Belding & Kamon 1973; Kamon 1976; Cottle et al. 2022; Vecellio et al. 2022; Wolf et al. 2021; Wolf et al. 2022; Wolf et al. 2023; Meade et al. 2024) identified the compensable–uncompensable transition visually based on curvature in the core temperature trace. Although pioneering, this graphical approach relied on subjective judgment and exhibited limited reproducibility, particularly when T_{cr} increased gradually or was affected by transient fluctuations. In the present study, the inflection point was defined objectively as the first time the smoothed T_{cr} slope reached or exceeded 0.25 °C/h and remained above this threshold thereafter. This criterion minimizes subjectivity, improves reproducibility, and aligns the detected inflection with the physiological onset of sustained uncompensable heat strain. To assess robustness, sensitivity analyses were performed using alternative slope thresholds (0.15, 0.20, 0.25, and 0.30 °C/h; see **Table S1** in Supplemental Material). Results confirmed that 0.25 °C/h provided stable and physiologically consistent estimates, whereas looser or stricter thresholds either advanced the transition unrealistically or delayed it toward higher core temperatures, potentially obscuring the early onset of uncompensable heat stress.

Results

Physiological interpretation of the model

The model conceptualizes the human thermoregulatory system as a first-order dynamic process governed by a single thermal time constant (τ), which defines the rate at which the body approaches thermal equilibrium. Two contrasting response regimes emerge depending on the relationship between the dwell interval (Δt) and this physiological time constant. When the dwell interval is short relative to the body's thermal inertia ($\Delta t \ll \tau$), core temperature does not fully equilibrate at each new humidity level before the next increment occurs. As a result, residual deviations between the instantaneous equilibrium temperature and the actual T_{cr} accumulate across successive steps. This cumulative lag manifests as an apparent acceleration in the rise of T_{cr}, producing an early inflection point that may be erroneously interpreted as a physiological limit of heat tolerance. Conversely, when the dwell interval is sufficiently long relative to the time constant ($\Delta t \gtrsim \tau$), T_{cr} has adequate time to approach equilibrium within each step, thereby minimizing transient deviations. Under these conditions, the temporal evolution of core temperature more accurately follows the equilibrium trajectory, yielding a smoother and more physiologically representative response to incremental humid heat stress.

Empirical findings

Critical environmental limits, expressed as critical wet-bulb temperature ($T_{w,critical}$), differed substantially depending on the duration of humidity increments (Δt). Core temperature increased most rapidly and reached critical levels earlier during the aggressive-ramp protocol than during the slow-ramp protocol. Across 14 participants, the mean critical T_w under the aggressive-ramp condition (Δt =5 min) was 29.9±1.6 °C, whereas the slow-ramp condition (Δt =60 min) yielded a significantly higher value (T_w =33.4±0.5 °C; P<0.001; mean difference: 3.4±1.9 °C; see **Figure 2** and **Figures S2–S3**). This divergence reflects the influence of thermal inertia on the apparent timing of physiological inflection. Consistent with the dynamic model, short ramp durations produce cumulative thermal lag, leading to an artificially early inflection in T_{cr}. In contrast, prolonged dwell intervals allow near-equilibrium to be achieved, shifting the apparent critical threshold to higher T_w values.

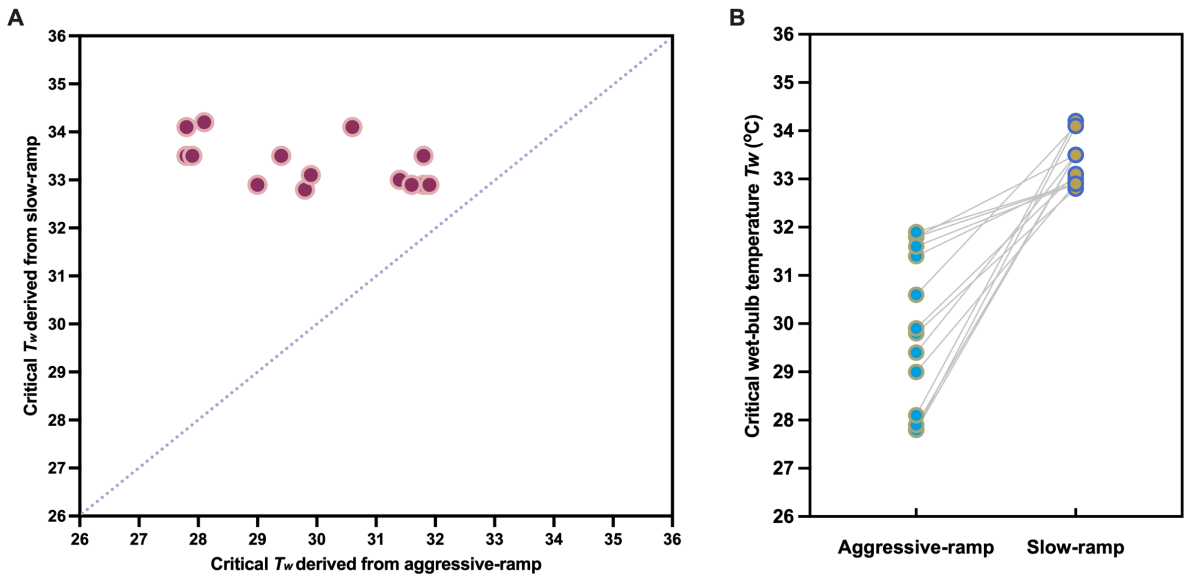

Figure 2 Critical wet-bulb temperatures (T_w) thresholds determined using two humidity-ramp protocols (aggressive vs. slow) at a constant dry-bulb temperature of 42 °C. The purple dotted line represents the line of identity ($y = x$). Data points lie consistently above this line, indicating that the aggressive-ramp protocol systematically yields significantly lower critical limits than the slower-ramp protocol across all 14 participants (mean difference=3.4±1.9 °C, 95% CI [2.3, 4.5]; two-sided P<0.001) with a very large effect size (Cohen's d=1.93, 95% CI [0.91, 2.63], see Panel **A**). This systematic underestimation likely arises from the shorter ramp duration (2% RH increase per 5 min), which induces a premature inflection point compared with the slower protocol (60 min per 6%/3% increase). Panel **B** shows a matchstick plot comparing paired critical T_w measurements from the two protocols. Each line connects the same participant's data under both conditions, with all lines trending upward from the aggressive-ramp to the slow-ramp values—clearly demonstrating that the aggressive-ramp protocol underestimates

the critical heat tolerance limit. The narrow distribution of slow-ramp data further indicates high measurement consistency, whereas the wider spread in the aggressive-ramp data suggests greater inter-individual variability and reduced precision under faster ramping conditions.

The time required for T_{cr} to stabilize under constant ambient temperature conditions was empirically determined at two levels of relative humidity (RH) increment (3% and 10%), following an initial full equilibration of T_{cr}. **Figure 3** shows the temporal evolution of rectal temperature (T_{cr}) following a stepwise 3% or 10% increase in relative humidity (RH) at a constant ambient temperature of 42 °C. In **Figure 3A**, a representative participant achieved a re-stabilized core temperature approximately 141 min after the fifth 3% RH increment, following the initial stabilization period. Consistently, during the interval between 90 and 300 minutes, T_{cr} required approximately 180 minutes to reach a steady-state (i.e., near 270 min; see **Figure 3B**). These observations indicate that, although the heat chamber completed a 3% or 10% RH increment within 3–5 minutes, physiological equilibration of T_{cr} occurred much more slowly than previously assumed. Collectively, these findings demonstrate that conventional humidity-ramp protocols with 5–10 min step durations are insufficient to allow T_{cr} equilibration and may therefore underestimate the true critical environmental limits.

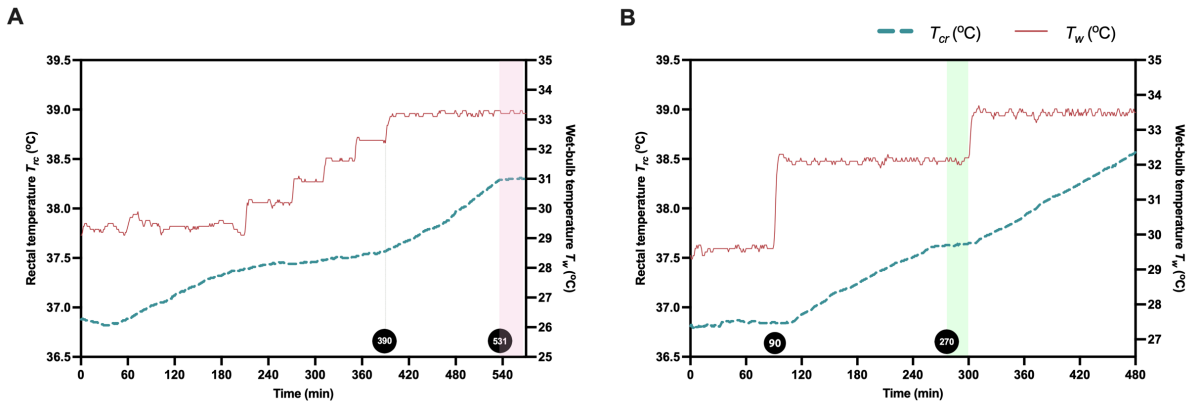

Figure 3 Time (τ) required for rectal temperature (T_{cr}) re-stabilization during stepwise increases in relative humidity (RH) following initial equilibration at a dry-bulb temperature of 42 °C. **A**, representative participant showing a 30-min stabilization period (shaded pink area) occurring at 531–570 min, after initial equilibration at 38% RH at 183 min, followed by five successive 3% RH increments. **B**, representative participant showing a 30-min stabilization period (shaded green area) occurring at 180 min, after initial equilibration at 38% RH, followed by a single 10% RH increase.

Sensitivity analysis

The first-order dynamical model highlights that the ratio $\Delta t/\tau$ (i.e., the ratio of step dwell time to the physiological time constant) determines whether T_{cr} can approach equilibrium at each stage. When $\Delta t/\tau \ll 1$, equilibration fails and residual deviations accumulate, yielding an apparent acceleration and a premature inflection in T_{cr}. This phenomenon constitutes a dynamic lag artifact rather than true physiological collapse.

Empirically derived estimates of the core temperature time constant (τ), obtained after an initial full equilibration of T_{cr} in the humidity ramp approach, ranged from approximately 2.35 hours to over 3 hours, depending on metabolic rate, hydration status, and thermoregulatory efficiency. Consequently, step durations of 5–10 minutes, commonly used in ramp-based studies, likely place participants in the aggressive-ramp regime, where such artefacts are inevitable (Belding and Kamon, 1973; Kamon 1976; Vecellio et al., 2022; Wolf et al., 2022; Meade et al. 2024b). We therefore recommend either empirical estimating τ for each cohort or performing sensitivity analyses to verify the robustness of threshold estimates across plausible τ values. **Table 1** presents the sensitivity of the dynamic response to step duration relative to the physiological time constant.

Table 1 Sensitivity analysis of the dynamic response to step duration (Δt) relative to the physiological time constant (τ).

Step duration (Δt, min)	**Physiological time constant (τ, min)**			**Predictive response characteristic**	**Artifact risk**
	120	**180**	**240**		
5	0.04	0.03	0.021	Rapid environmental progression; core temperature lags markedly	High
10	0.08	0.06	0.042	Core temperature lags markedly; transient accumulation between steps	High to moderate
60	0.5	0.33	0.25	Partial or near equilibration for faster responders; moderate residual lag; slower for large τ	Low
120	1.0	0.67	0.50	Substantial or full equilibration across steps; minimal residual error	Very low

Note: Artifact risk is categorized into four levels: **High** (substantial accumulation of lag between steps), **Moderate** (moderate lag with transient accumulation), **Low** (minimal lag and near steady-state equilibration), and **Very low** (no significant artifacts; full equilibration); The key determinant of dynamic distortion is the dimensionless ratio $\Delta t/\tau$, where Δt represents the dwell duration and τ the physiological time constant of core temperature equilibration. Smaller values of this ratio indicate more rapid environmental progression relative to the body's thermal response. When $\Delta t/\tau \ll 1$ (e.g., 0.01–0.20), the environment changes faster than the thermoregulatory system can respond, leading to accumulated lag and an apparent early inflection in T_{cr}. When $\Delta t/\tau \approx 1$, full equilibration occurs and

transient effects are greatly reduced. When $\Delta t/\tau > 0.3$–0.5, the response effectively reaches near quasi-steady state, and dynamic lags and associated artifacts are largely eliminated.

Discussion

This study demonstrates that the apparent "critical point" observed in humidity ramp protocols is strongly influenced by the temporal structure of the environmental change. Our first-order dynamic model reveals that when the rate of relative humidity (RH) increase exceeds the body's intrinsic thermal response time (Cramer et al. 2022), the rise in core temperature (T_{cr}) accelerates across successive steps. Under such conditions, frequent small humidity increments force the body to continually "chase" a moving target equilibrium, producing apparent inflection points that reflect dynamic lag artifacts rather than true thermoregulatory failure. Conversely, when each step is maintained long enough to permit partial or full equilibration, these transient discrepancies diminish, and the T_{cr} trajectory becomes smoother and physiologically interpretable.

The ratio of step duration (Δt) to the thermal time constant (τ) offers a dimensionless index of ramp adequacy. When $\Delta t/\tau \ll 0.2$, dynamic lag dominates, yielding premature inflections and artificially low apparent thresholds; Ratios between $0.2 \leq \Delta t/\tau < 0.5$ allows partial equilibration, while $\Delta t/\tau \gtrsim 0.5$ approximates quasi-steady-state conditions with minimal artifacts. Empirically, a ratio near 0.3 achieved partially stable core temperature responses without excessively prolonging the protocol. Estimating τ during the initial equilibration phase can therefore guide individualized ramp pacing, while post hoc dynamic correction models may further approximate equilibrium T_{cr} values without requiring longer exposures.

Although the model simplifies the human thermoregulatory system to a first-order process characterized by a single time constant and linear heat exchange, it effectively captures the essential delay dynamics linking environmental perturbations to physiological responses. Human thermoregulation involves inherently nonlinear processes such as sweating kinetics, core–skin coupling, and delayed feedback in vasomotor and sudomotor control (Wyss et al. 1974; McCook 1965; Bini et al. 1980; Taylor et al. 2019). Nonetheless, the present first-order framework isolates the temporal dimension of these higher-order complexities. As such, it provides a tractable and physiologically interpretable foundation for refining humidity-ramp protocols and improving the validity of human heat tolerance assessments.

The classic formulation by Belding and Kamon (1973) emphasized the necessity of initial equilibration, noting that core temperature could require "more than 2 hours to re-stabilize" at critical vapor pressure levels. To reduce the laborious nature of the full steady-state method, they introduced a shortcut approach—increasing humidity by approximately 1 mm Hg (≈2% RH at 42°C) every 10 minutes following an initial hour of equilibration. While this adjustment acknowledged the importance of stabilization upon chamber entry, it did not extend the principle to subsequent humidity increments. As a result, the continuing influence of physiological equilibration on determining critical environmental limits (CELs) was not fully appreciated. Our empirical data demonstrate that this assumption is invalid: even small humidity increases required approximately 2.35–4.0 h for T_{cr} to restabilize (**Figure 3**). Hence, shortcut ramp protocols progress much faster than the body's thermal time constant, leading to premature inflection points that misrepresent the true onset of uncompensable heat stress. Consistent with this interpretation, studies employing short dwell times (Vecellio et al. 2022; Wolf et al. 2022, 2023; Cottle et al. 2022; Meade et al. 2024) have reported $T_{w,critical}$ values of 26.0–32.3 °C in young adults—substantially lower than steady-state-derived thresholds of 33–34 °C (Wang et al. 2025a).

Comparison between the aggressive (Δt = 5 min) and slow (Δt = 60 min) ramp regimens further underscores the importance of temporal pacing in accurately estimating CELs. The slow-ramp protocol yielded $T_{w,critical}$ =33.4 °C, aligning closely with the physiologically inferred compensable–uncompensable boundary, whereas the aggressive-ramp underestimated this threshold due to thermal inertia. At 42 °C, a 3% RH increase corresponds to an ~0.7 °C rise in T_w—enough to overshoot the narrow 33–34 °C transition zone, highlighting the challenge of precise determination without prolonged steady-state exposures.

A plateau substudy was initially planned to isolate transient thermal dynamics by maintaining each humidity step until T_{cr} reached steady state, defined as $|dT_{cr}/dt| \leq 0.1$ °C over 30 minutes. However, this would have required more than 10 hours of continuous exposure, posing substantial ethical and logistical constraints (a methodological illustration is shown in **Figure S4**). Given prior evidence situating the compensable–uncompensable transition around T_w = 33–34 °C, the slow-ramp protocol provided a physiologically valid yet practical alternative to exhaustive steady-state trials. Nevertheless, without prior knowledge of this range, designing a valid slow-ramp protocol remains challenging, as even modest RH increments can produce disproportionately large changes in wet-bulb temperature at elevated dry-bulb temperatures.

Physiological and methodological implications

We propose the ratio $\Delta t/\tau$ as a dimensionless index of protocol adequacy, where Δt denotes the dwell duration of each humidity step and τ represents the physiological time constant for core temperature equilibration. When $\Delta t/\tau < 0.2$, ramp protocols induce pronounced dynamic artifacts due to incomplete equilibration; values of $0.2 \leq \Delta t/\tau < 0.5$ allow partial equilibrium responses, whereas $\Delta t/\tau \geq 0.5$ approximates quasi–steady-state conditions with minimal artifacts. Empirically, a ratio of approximately 0.3 was sufficient to achieve partially stable core temperature responses without unduly prolonging exposure. Estimating τ from the exponential rise of T_{cr} during the initial equilibration phase allows individualized ramp pacing that aligns with each participant's thermophysiological response capacity. Alternatively, post hoc dynamic correction models can be applied to approximate equilibrium core temperature ($T_{cr,eq}$) without substantially extending experimental duration.

This framework explains why rapid humidity-ramp protocols consistently yield artificially low CELs and underscores the need to standardize ramp parameters across laboratories. Inflection-based thresholds should therefore be interpreted as transient artifacts rather than steady-state physiological limits. In this context, prolonged steady-state exposures remain the definitive benchmark for defining true compensability and for calibrating predictive models, occupational exposure limits, and wearable heat-strain algorithms (Buller et al. 2018; Vanos et al. 2023; Xu et al. 2024).

The methodological implications are substantial. Conventional humidity-ramp studies implicitly assume adequate equilibration between increments; however, our data demonstrate that typical 5–10 min dwell times are far shorter than the body's equilibration period. At $T_w \approx$ 31.7 °C (T_{db} = 42 °C), T_{cr} required approximately >3 hours to re-establish steady-state conditions following a 10% RH increase during the first stepwise increment (**Figures 3D–3F**). Consequently, the apparent "inflection point" observed in ramp experiments predominantly reflects cumulative transient heat storage rather than the true transition to uncompensable heat stress. This dynamic lag produces artificially steep T_{cr} trajectories and a systematic underestimation of human heat tolerance.

Accordingly, humidity-ramp protocols should be viewed as rapid yet conservative approximations of compensability thresholds. To derive physiologically valid estimates, each step must be maintained until at least partial steady-state equilibration is achieved. Although time-consuming, this approach provides the most accurate representation of environmental compensability. Thus, prolonged steady-state exposure remains the methodological gold

standard for quantifying human heat tolerance (Schlader et al. 2020; Wang et al. 2025a; Wang et al. 2025b).

Limitations and future directions

The first-order model applied here assumes a constant metabolic rate and uniform body temperature distribution, which does not capture nonlinear sweating kinetics, spatial core–skin temperature gradients, or feedback delays in vasomotor and sudomotor control. Nevertheless, this simplification effectively isolates the dynamic lag mechanism that underpins the present findings. Future work should quantify sex- and age-related variability in the physiological time constant (τ), examine the effects of exercise intensity on thermal response dynamics, and characterize nonlinear changes in evaporative efficiency under high-humidity conditions (Shoenfeld et al. 1978; Kenney and Munce 2003; Wang et al. 2025a). Extending this framework to diverse populations and coupling empirical measurements and with advanced thermophysiological modeling will enhance the physiological fidelity of critical heat stress thresholds and improve their integration into predictive climate–health risk models.

Conclusions

Humidity-ramp protocols have long served as practical tools for assessing safe work limits under hot conditions and have since been extended to estimate human heat tolerance or critical environmental limits. However, their validity is fundamentally constrained by thermal disequilibrium. When the rate of environmental change exceeds the body's intrinsic capacity for physiological equilibration, apparent inflection points primarily reflect dynamic lag rather than true uncompensability. Critical environmental limits derived from short ramp durations should therefore be interpreted with caution. Accurate quantification of human heat tolerance requires either prolonged steady-state exposures or dynamic correction models rigorously validated against such reference conditions. Until these corrections are standardized, humidity-ramp protocols should not be used as stand-alone methods for defining physiological heat tolerance limits. Prolonged steady-state exposure remains the most reliable approach for defining the true human heat tolerance limit and should continue to serve as the methodological benchmark for future heat tolerance research.

Author contributions

F.W. conceived the study, developed the model, designed experiments, prepared figures and illustrations, acquired funding, and drafted the manuscript. Y.X. performed experiments, analyzed data, prepared figures (Figures S2 and S3), and revised the manuscript. H.W., M.C., X.H., and B.W. performed experiments, analyzed data, and revised the manuscript. All authors reviewed and approved the final version of the manuscript.

Acknowledgments

This research study was supported by the National Excellent Young Scientist Program (Grant No. 6119924022, to F.W.) and the Shaanxi's "Sanqin Scholars" Plan Program (Grant No. 2050225003, to F.W.). We sincerely thank all participants of the study for their time and invaluable contributions.

Conflict of interest statement

The authors declare no conflicts of interest, financial or otherwise.

Data availability statement

Data are available upon request from the corresponding author (F.W.).

Supplemental material

Supplemental material has been provided and uploaded to the peer review system.

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